(Preprint) AAS 18-152

CASSINI ORBIT DETERMINATION OPERATIONS THROUGH THE FINAL TITAN FLYBYS AND THE MISSION GRAND FINALE (FEBRUARY 2016 – SEPTEMBER 2017)

Julie Bellerose,[*] Duane Roth,[**] Dylan Boone,[+] Zahi Tarzi, [+] Rodica Ionasescu, [+] Kevin Criddle[+]

This paper reports on the orbit determination performance for the final 1.5 years of the Cassini Solstice mission, including the mission's Grand Finale. During this period, Cassini encountered its final eleven targeted flybys of Titan (T116-T126) and executed its last 62 orbits of Saturn. In these final months, the spacecraft's inclination was gradually raised from near equatorial to near 63 degrees, critical inclination, to prevent the line of apsides from rotating out of Titan's orbital plane. Critical inclination enables continued Titan flybys, the last of which places Cassini on an impact trajectory with Saturn, thereby satisfying planetary protection requirements. In this reporting period, the orbit period moved from 16 days to nearly 32 and, for the final 6 months, it was brought down to less than 7 days. By design, the spacecraft entered the Saturn atmosphere on its final orbit and vaporized on September 15, 2017. We also report on the particular challenges associated with a stellar occultation, a flyby of Saturn's rocks, and the last revolutions of the mission's Grand Finale.

INTRODUCTION

Cassini has been orbiting Saturn since 2004. Through its prime mission and two extended missions, the spacecraft explored the planet's mysteries and flew by thirteen of its sixty-two moons. Cassini began its second extended mission, referred to as the Solstice Mission, in September 2010. Among several objectives, the seven-year extension was designed to allow continuous observations of Saturn and its moons between Saturn's southern and northern summer solstices. After its last equatorial phase in the summer of 2015, the trajectory was designed to slowly increase the orbit inclination to 63 degrees for the final Ring-Grazing and Grand Finale orbits, as shown on Figure 1.

Thirteen years after arriving at Saturn, Cassini's streamlined navigation operations adjusted to the short period orbit and the long gaps between encounters. The last transfer from Titan-125 (T125) to T126 spanned five months, where three of the four last maneuvers were separated by a couple of months. Spacecraft operations included more small thruster activities for science and reaction wheel management, which further increased Cassini's position uncertainty at its final Titan encounter and during the Grand Finale orbits.

---

[*] Cassini Orbit Determination Lead, Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, 91109.
[**] Cassini Navigation Chief, Jet Propulsion Laboratory, California Institute of Technology.
[+] Cassini OD Analyst, Jet Propulsion Laboratory, California Institute of Technology.

Continuing from where the previous report left off and covering through end of mission, this paper completes the reporting of Cassini orbit determination mission operations[1]. The last year and a half of the Cassini mission was made entirely of Titan encounters, with a few non-targeted distant icy satellite flybys of note. The F-ring orbits formally started with T125 in December 2016, while the Grand Finale orbits lasted from T126 in April 2017 to the end of mission in September 2017. This paper reports on the navigation flyby accuracy relative to our encounter predictions, and some particular events that required the navigation team's attention, namely, a stellar occultation by Enceladus, a flyby of one of Saturn's rocks, and Saturn's atmospheric density being about 300% denser.

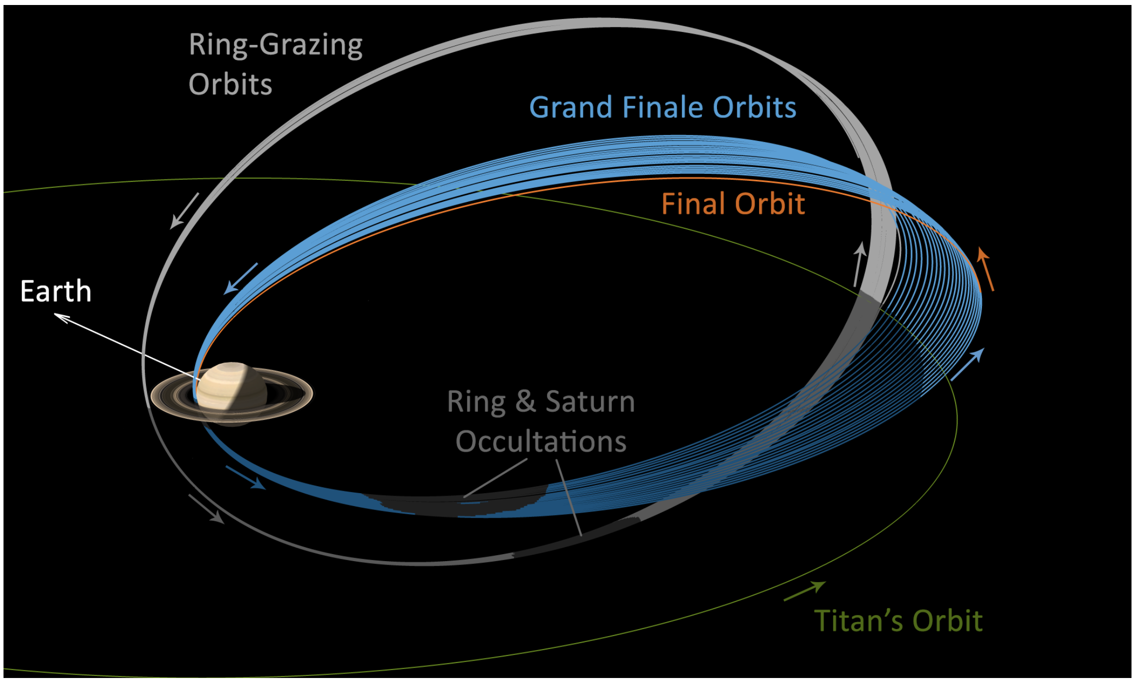

Figure 1. Cassini's F-ring and Grand Finale orbits.

NAGIVATING THE LAST YEAR AND A HALF

Highlights of Recent Orbit Determination Changes

The Cassini navigation team includes two sub-teams: the orbit determination (OD) team and the flight path control team (Maneuver). The goal of the team is to deliver the spacecraft to pre-determined satellite flyby target locations at specified times based on a design reference trajectory[2].

The OD team is responsible for computing the spacecraft orbit, both in the past and predicts of its future course, along with the associated error estimates. The reconstructed and predicted spacecraft ephemeris are disseminated to the rest of the flight team to support spacecraft operations and science activities. Over the first eleven years of Saturn orbital operations, five papers have covered Cassini's OD performance[1,3-6]. The last 10 months could be described as a whole new mission compared to the lifetime of Cassini; the navigation team still had to adapt to unmodeled errors and unforeseen changes. Various modeling changes had to be made, from dynamic modeling and mapping, to reporting and communicating with other project teams.

Orbit determination solutions are typically computed over arcs defined by an epoch set at the apoapse prior to a given flyby, and an end epoch after the following flyby. Three maneuvers were placed in between any two particular flybys, one to "clean up" errors after the first flyby while the following two targeted the second flyby[1]. Typical arc lengths varied between a few weeks to a couple months. The last two Titan flybys were an exception, being separated by 5 months.

The OD process is shown in Figure 2, with filter parameters in Table 1. Inputs include radiometric tracking data (2-way Doppler and range), media calibration parameters which affect the data, parameters representing the exact time and location of the Earth tracking stations, and dynamic forces acting on the spacecraft, such as thrusting events. After updating a priori models, a linearized least-squares estimation process provides estimates for Cassini's orbit, along with parameters of the Saturnian system, such as Saturn's gravity field, and orbits and point masses of selected satellites (if needed). The Saturn system model includes 10 of Saturn's 62 moons, with the closest to Saturn being Mimas, and farthest Phoebe. In addition, non-gravitational forces which affect the spacecraft are also estimated, including the Delta-V from small burns, acceleration from radioisotope thermoelectric generator heating, and zero-mean stochastics accelerations for any remaining small unmodeled forces. During the Grand Finale, a drag coefficient was estimated for Saturn's atmospheric density. The complete list of filter parameters is shown in Table 1. After a few iterations to manage non-linearities, the converged solution is delivered to the Maneuver team for orbit trim maneuver (OTM) design.

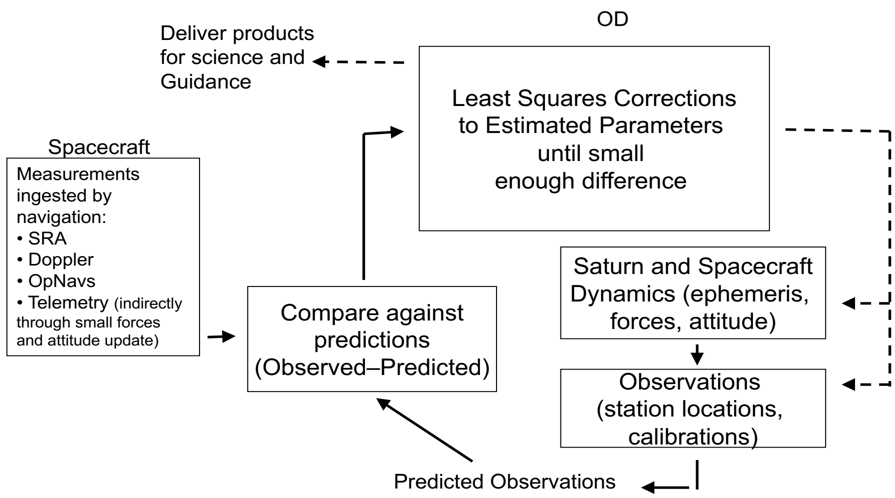

Figure 2. Orbit Determination process.

Table 1. Estimated and consider parameter uncertainties, with latest OTM errors taken from Ref 7 and 8. *Less visited satellites such as Hyperion, Iapetus, Phoebe have 2-5 times higher σ than icys.

Estimated	Apriori 1 σ error	Consider	Apriori 1 σ error
Cassini states	< 5 km, < 20 cm /s	Station locations	2 – 5 cm
DV small burns	0.25 mm/s – 1.2 mm/s	Troposphere	1.0 cm wet, 1.0 cm dry
OTM (ME)	0.02% proportional, 3.5 mm/s fixed	Ionosphere	5 cm day, 1 cm night
OTM (RCS)	0.4% proportional, 0.5 mm/s fixed	Earth orientation	10 cm per axis
Stochastics	5 e -13 km/s2		
Transponder bias	500 m		
Satellite*	<0.1 km Titan, <km icys		
Saturn	0.2 km		
Saturn J2 – J8	< 0.01%		
Saturn pole (RA, DEC)	< 0.01%, < 0.0001%		
CD Saturn	100%		

The Last Ten Titan Flybys: How Did We Do?

At the beginning of 2016, Cassini's trajectory was designed to slowly increase Cassini's inclination. Formally named "Inclination-3", this phase was to bring Cassini's inclination from near zero degrees with respect to Saturn's equatorial plane, to above 63 degrees for orbit stability. Starting with T114, each subsequent Titan flyby added up to 10 degrees to the orbit inclination. See the entire inclination profile for the Solstice mission in Figure 3.

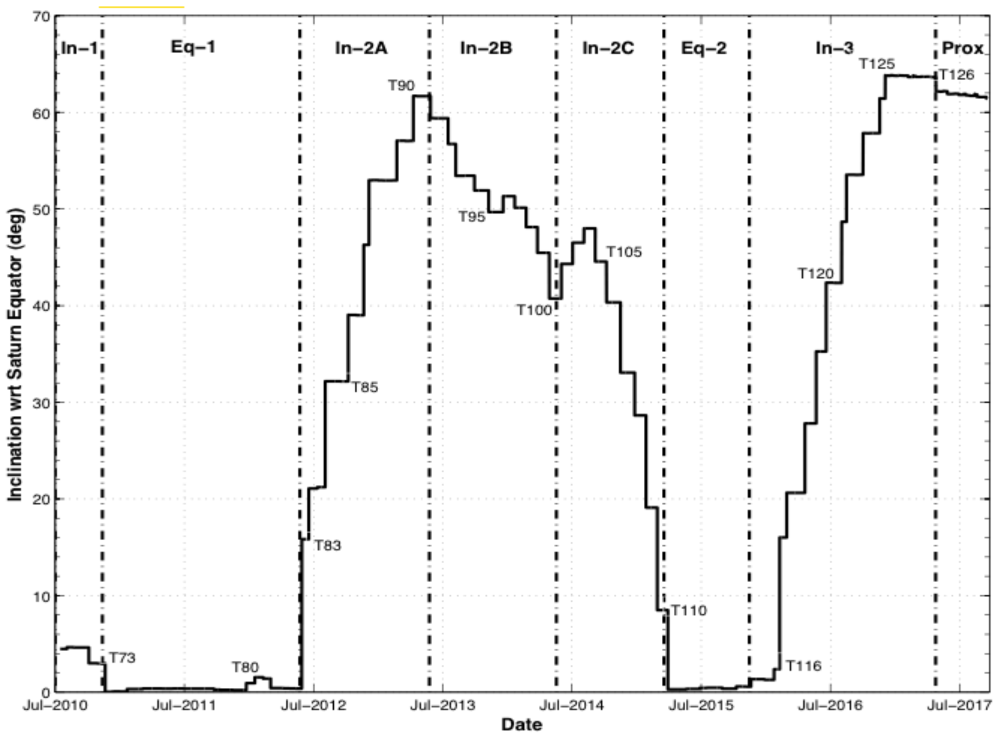

Figure 3: Cassini's Solstice mission inclination profile[9].

We start this OD performance paper in February 2016 with T116, which was a distant flyby at 1398 km in altitude. Ten more Titan flybys would follow, varying in altitude from 3158 km down to 975 km. On a scientific level, those last 10 flybys also allowed the Cassini team to transition from Saturn equatorial science to a highly elliptical geometry, bringing the spacecraft to closer than ever approaches to Saturn. The Inclination-3 phase reached an inclination above 60 deg at T124, a 1565 km altitude flyby. This encounter was specially designed for the radio science subsystem, and constituted their last Titan surface observation.

T125 brought Cassini's orbit periapse to grazing distance on the outskirts of the F-ring, with an orbit period about a week long. Similarly, T126 reduced the periapse distance even more, making Cassini dive between Saturn and its innermost ring, the D-ring, every 6.4 days. The 22.5 orbits after T126 were deemed the "Grand Finale", as this was the final phase of the Cassini mission. The Grand Finale ended with Cassini being safely disposed within Saturn.

The encounter performance is reported in terms of miss distance at the time of the flyby. To compute the 3D miss, at each encounter the post-flyby reconstructed states is differenced from the predicted ones based on the trajectory from the approach maneuver data cutoff. Table 2 reports the 3D encounter miss in column 4 and the corresponding 3D sigma level based on the state error covariance in column 5. The 3D error sigma is the Mahalanobis distance, or the scale factor that must be applied to the one-sigma error ellipsoid such that the scaled ellipsoid just encompasses the miss vector. Column 6 lists the probability of lying within the scaled 3D covariance ellipsoid, and is computed through a Gauss error function.

The first half of 2016 was marked by large misses at Titan, especially for T116, T119 and T120 in Table 2. This was coincident with use of an updated Saturn pole model that included trigonometric terms instead of only linear terms. In retrospect, this model was less accurate than its predecessors. To predict Titan encounters better, the Saturn system's parameters described in 2.1 were put back in the estimated parameters list with looser a priori uncertainties. They had been "considered" from 2013 to early 2016, where models and uncertainties are accounted for but models are not updated[11]. Following this change in OD process, Titan encounter performance improved with 3D miss less than 1 km. The very last flyby miss was affected by an overly optimistic filter in the hundred-meter level.

Table 2. Encounter Summary, Feb 2016 to April 2017.

Target	Date	Altitude (km)	3D error (km)	3D sig	Prob. of better solution (%)	Comment
T116	01-Feb-16	1398	2.29	4.8	100	Software transition
T117	16-Feb-16	1018	0.35	2.2	81	Sat375
T118	04-Apr-16	990	0.41	0.9	17	
T119	06-May-16	969	2.44	5.8	100	E16 5 mos prior
T120	07-Jun-16	975	1.06	2.9	96	
			1.17	7.7	100	
T121	25-Jul-16	975	0.77	2.8	94	Sat389 + Saturn
T122	10-Aug-16	1698	1.11	0.5	3.3	System estimated
			0.20	0.8	11	
T123	27-Sep-16	1775	0.14	1.6	53	
T124	13-Nov-16	1585	0.37	1.2	29	Last RSS flyby
T125	29-Nov-16	3158	0.33	0.3	0.8	
			0.12	1.1	24	
T126	22-Apr-17	1581	0.32	3.4	99	Too good to be true!

CHALLENGES, AND THE END

Stellar Occultation by Enceladus

In March 2016, a stellar occultation by Enceladus and its plume impacted the navigation activities associated with the design of OTM-443[10]. This occultation was a high priority science observation. For this to be successful, the uncertainty of the projection of the Cassini's states onto the plane perpendicular to the Cassini-star vector during the time of occultation needed to remain outside the projection of Enceladus' solid body shape on this same plane near the south polar crossing. A separation of 15-40 km was ideal. This impacted the maneuver implementation policy; if for some reason, Cassini's prime uplink opportunity is missed, the backup maneuver is then radiated.

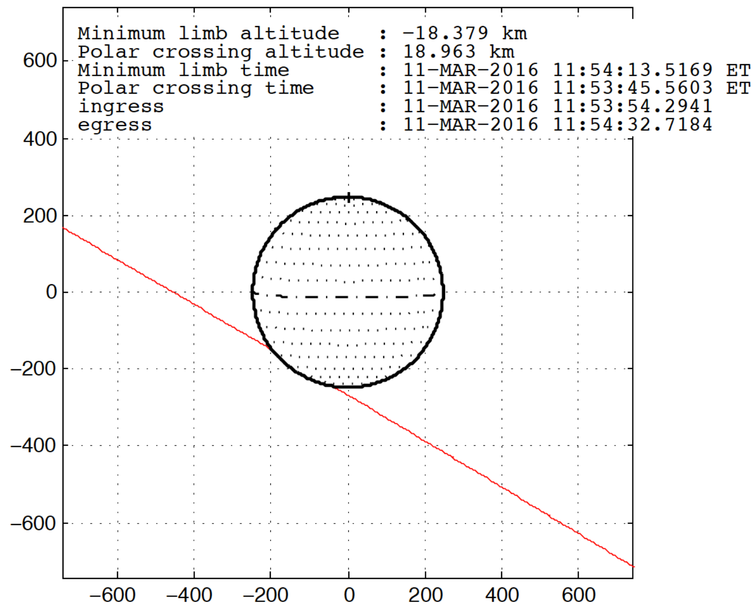

Figure 4: Enceladus occultation, as viewed from Canis majoris[8].

The observation geometry required capturing a plume occultation at Enceladus' south pole just prior to occultation by Enceladus' solid body. As seen in Figure 4, where the red line is Cassini's trajectory, there was virtually no margin for error: too high and the plume occultation is replaced with an Enceladus solid body occultation - too low and the occultation passes through a less dense portion of the plume. Since the last control point for this activity was the T117 clean-up maneuver OTM-443, uncertainties at data cutoffs for the prime and backup maneuver opportunities were mapped to the occultation time and examined. The mappings were obtained in a frame where the Z component is defined along the spacecraft angular momentum direction relative to Enceladus, X in the direction of the spacecraft relative to Enceladus center, and Y completing the right hand rule. Since we are interested in the observation across the plume, the uncertainty along the momentum direction is the important parameter.

Hence, in mid-Feb 2016, the team decided to forego the prime maneuver and perform the backup. It was noted the uncertainties dropped a significant amount, more than half, by waiting for the backup maneuver data cutoff since more data could be processed to resolve the Titan flyby. Fortunately, the cost of possibly missing the maneuver altogether dropped from 0.5 m/s to about 150 mm/s as Titan flyby errors became better resolved. This was largely because OTM-444 was already a large targeting maneuver (8 m/s), and could easily absorb the trajectory error imparted by missing the much smaller OTM-443 backup maneuver. In the end, the occultation was successful with 30 seconds of star occulted by the plume.

Epimetheus Flyby: getting an unexpected nudge

The T125 flyby brought the trajectory's periapse to the edge of the F ring providing new opportunities to observe some of Saturn's inner moons. Cassini's periapse was now as close as 2.47 Saturn radii (R_s) from Saturn's center while its apoapse was 21.32 R_s. In particular, such proximity allowed for imaging Epimetheus and Janus. Because of their negligible dynamical effect on other moons, Epimetheus and Janus were considered as "rocks" and thus their point mass gravitational perturbation on the spacecraft was not previously modeled. Little did we know those small moons would provide enough gravity assist to be noticed.

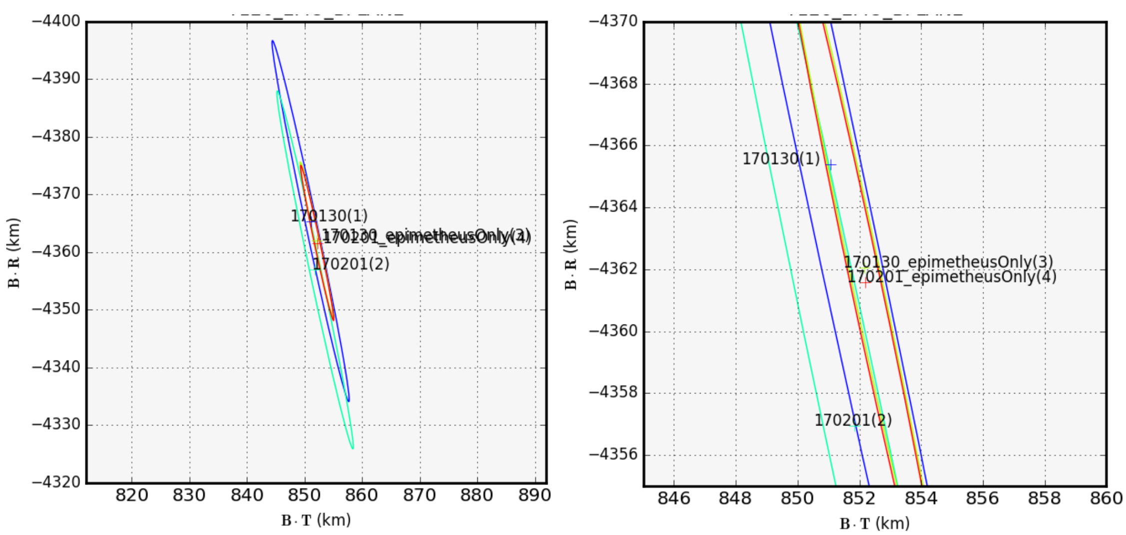

Figure 5: OD solutions with/without Epimetheus gravity modeled, zoomed in on the right.

On January 30th 2017, Cassini performed a distant flyby of Epimetheus, at a close approach altitude of 3567 km, and returned breathtaking images. The OD team noticed a significant Doppler signature pointing to discrepancies between the pre and post-flyby orbit solutions, and a shift of almost 10 km on the T126 B-plane, visible in Figure 5. Here we can see that the post periapse solution, 170201, is slightly off from the pre-periapse solution, 170130. There was a sizable spacecraft thrusting force to counter a wheel turn right before periapse for science observations, and so the unexpected signature was initially attributed to a possible difference between the predicted and telemetry values for translational Delta-V caused by that particular bias. The filter estimated a velocity change of 2 mm/s instead of the expected 0.25 mm/s. However, the post-bias telemetered values agreed well with predicted values. In addition to questionable estimates of the biases, the OD solution showed significant corrections to the Saturn gravity field harmonic coefficients, J4 and J6, estimating them 3.5 sigma higher, which hinted to a dynamical mismodel.

From these observations, it seemed more likely the moon had slightly deflected Cassini's trajectory. Back of the envelope calculations indicated a gravity assist Delta-V on the order of a couple of millimeters per second and that the flyby had indeed played a role in Cassini's velocity change.

Knowing Cassini and Epimetheus states at the time of the moon encounter, one can compute the turning angle and the change in velocity relative to Saturn. The turning angle with respect to Saturn is defined as

$$\delta = 2\sin^{-1}\left(\frac{1}{e_{hyp}}\right),$$

where e_{hyp} is the eccentricity of the hyperbola at Epimetheus, greater than 1, defined as

$$e_{hyp} = 1 + \frac{r_{rf} v_\infty^2}{\mu_{Epi}}.$$

With respect to Epimetheus, v_∞ is the hyperbolic excess velocity, constant relative to Epimetheus. It is the difference between the velocity of Cassini at Epimetheus flyby relative to Saturn and the velocity of Epimetheus relative to Saturn.

$$v_\infty = v_{CES} - v_{ES}$$

Choose a frame where u_p is a unit vector in the direction of Epimetheus velocity, and u_r perpendicular to it in the plane of the flyby. Then using Cassini's flight path angle, we can express

$$\overrightarrow{v_{CES}} = v_{CES}\cos(\phi_{fpa})u_p + v_{CES}\sin(\phi_{fpa})u_r.$$

ϕ_{fpa} is computed from Cassini's orbit angular momentum at the encounter,

$$\phi_{fpa} = \cos^{-1}\left(\frac{h}{r_{atE}v_{atE}}\right).$$

The angular momentum is

$$h = \sqrt{\mu_S a(1-e^2)}.$$

The velocity vector angle of v_∞ with respect to Epimetheus is determined as

$$\phi = \sin\left(\frac{\overrightarrow{v_\infty}\mu_r}{||v_\infty||}\right).$$

Then the post flyby velocity in the direction of u_r becomes,

$$v_\infty^+ = v_{\infty\cos}(\delta - \phi) + v_\infty sin$$

Finally, we have

$$v_{fb} = v_\infty^+ + v_{Epi}.$$

Querying Cassini, Saturn and its moons ephemerides, we use: r_{atEpi} = 149831.89 km, v_{atEpi} = 21.31 km/s, μ_{Epi} = 0.035 , μ_S = 37.931e6 km^3/s^2, v_{Epi} = 15.7119 km/s. The Delta-V contribution from the gravity of the moon is computed as $v_{atEpi} - v_{fb}$, resulting in the order of a couple mm/s, which is the magnitude of what the team had observed.

When mapped on the T126 B-plane, as seen in Figure 7, the solution which includes the Epimetheus gravity, 170130_Epimetheus and 170201_Epimetheus, before and after the periapse respectively, are consistent, as compared to the associated solutions without Epimetheus' gravity. Another similar flyby of Epimetheus was scheduled 3 weeks later with a close approach of 8,018 km, and one of Janus at an altitude of 12,000 km was planned for April 12th, which would also be affecting Cassini's trajectory. The OD team updated their models to include them both.

Grand Finale Challenges and the Last Five Revs

The Grand Finale provided an incredible opportunity for close-up science of Saturn, its rings, and some of its inner satellites. On April 22nd, T126 brought Cassini's orbit periapse just inside the D-ring, making Cassini dive through the gap between Saturn and the rings every 6.4 days. This is shown in Figure 6. The navigation requirements during those last five months were relaxed due to the absence of satellite encounters and the stable inclined orbits. From a science request, three maneuvers were added in order to keep Cassini's trajectory dispersions below 250 km. Those maneuvers, OTMs 470-472, targeted periapses 3, 13, and 16 position coordinates to satisfy science requests[12].

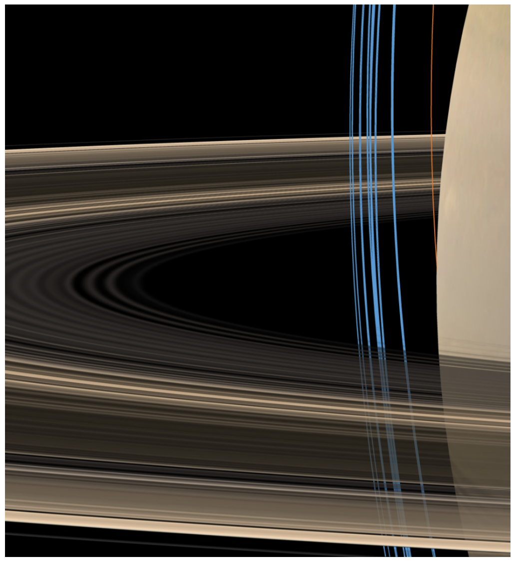

Figure 6: Cassini's dives during the Grand Finale.

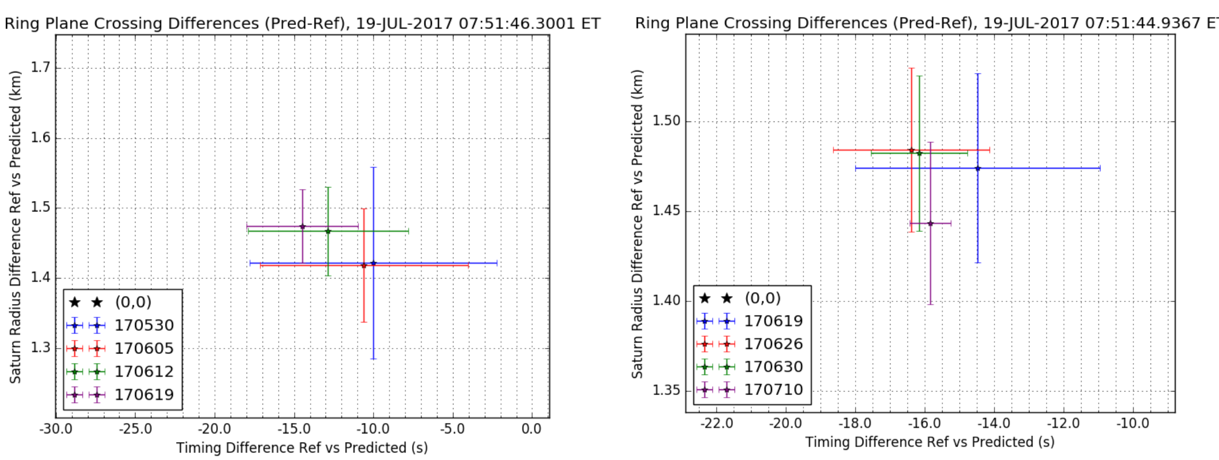

Figure 7: Ring plane crossings between May 30th and June 19th 2017 (left), and between June 19th and July 10th 2017 (right).

The Grand Finale turned out to be one of the most interesting and challenging phases for the OD team. In particular, the OD team noted drift in the timing of the ring plane crossing compared to the reference trajectory. Early assessments indicated some drag-like effects, where some fictitious Delta-V could be estimated between 0.2 and 0.5 mm/s. These timing drifts are visible in Figure 7 above, where solutions drifting to the right indicate a drag, and to the left indicate a kick, respectively. High fidelity analyses are still ongoing to see if the unexpected Delta-V observed can be attributable to gravity or atmospheric mismodeling. Beside the intrinsic science value of the unknown, the consequences were not so dramatic but did make the Flight Path Control team investigate alternate ways of minimizing the overall dispersions[13].

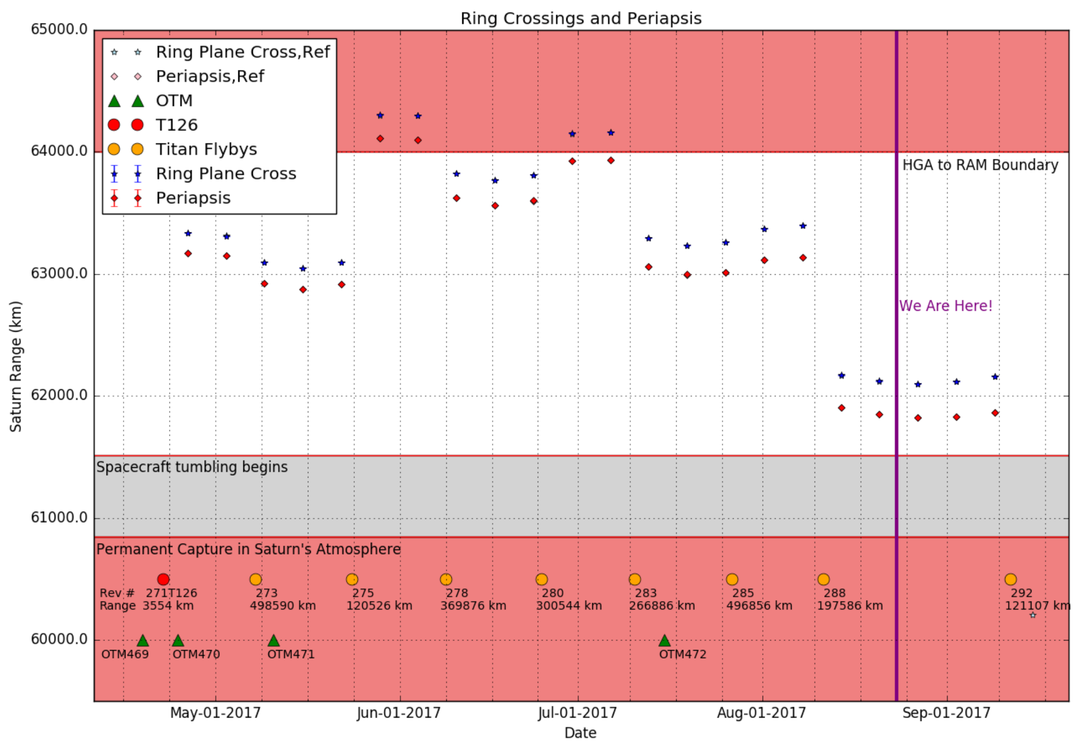

Figure 8: Saturn crossings during the Grand Finale.

The very last five revolutions around Saturn were a true test for the whole Cassini project. The finale was designed to graze Saturn's upper atmosphere at an altitude just below 62,000 km, as seen in Figure 8. Due to Saturn atmospheric density uncertainty, the project had implemented three placeholders for what was referred to as pop-up and pop-down maneuvers, OTM-473 to 475. Those maneuvers were designed to nominally raise or lower Cassini's next periapse altitude by an amount dependent on the density modeling error. If, during the first of those atmospheric grazings, Cassini thrusters' duty cycle turned out to be too high, indicating too much thruster activity to maintain attitude, a pop-up would be implemented. Alternatively, if the atmosphere turned out to be much less than expected, the science teams had requested the capability to go deeper in the atmosphere for better science.

After Cassini's first of those five dives, the atmosphere estimated to almost three times denser than the nominal model. With the mission planning team estimating the duty cycle for the follow-on periapse nearing 70% (80% was set as the maximum limit), the pop-up maneuver was canceled.

Eventually, the next two pop-down maneuvers were also canceled because extraordinary science was already being gathered at existing altitudes.

The OD team's estimated Saturn's atmospheric density varied from 220% to 260%. Since the density itself is not estimated, this is shown through the Cassini spacecraft's drag coefficient, CD, listed in Table 3. Note that the nominal CD is 2.1. Specifics of the Saturn's atmospheric modeling are detailed in Boone et al[14].

Table 3. Saturn's atmospheric density estimation through Cassini's CD.

Saturn periapse times (ET)	Post-fit sigma	CD estimated value
14-AUG-2017 04:24:12	0.24	5.42
20-AUG-2017 15:24:09	0.17	5.76
27-AUG-2017 02:19:19	0.12	4.84
02-SEP-2017 13:14:09	0.16	5.34
09-SEP-2017 00:10:54	0.20	5.34
15-SEP-2017 10:55:16	0.48	4.98

The official loss of signal time on September 15 are listed in Table 4 for the Attitude and Articulation Control Subsystem (AACS) predicted altitude, and from the last telemetry and X/S band Doppler data received, with corresponding altitudes, ranges, and latitudes with respect to Saturn.

Table 4. Loss of signal on September 15th. SCET is Spacecraft time whereas ERT is Earth received time.

	UTC SCET epoch	UTC ERT epoch	Altitude (km)	Range (km)	Latitude (deg)
AACS prediction	10:31:49	11:55:16	1.39731e+03	6.14846e+04	9.36
X telemetry	10:31:51	11:55:18	1.38464e+03	6.14741e+04	9.30
X carrier	10:32:10	11:55:37	1.26678e+03	6.13756e+04	8.77
S carrier	10:32:17	11:55:44	1.22431e+03	6.13401e+04	8.58

Fun fact: while providing the best science opportunities, those last five dives gave Cassini's public relations office a few headaches as the loss of signal time uncertainty varied until the last few days. All clocks needed to be synchronized!

CONCLUSION

The Cassini's trajectory was the most complex trajectory flown in the history of spaceflight, and the mission's final year gave everyone great wonders on all levels. For the first time, Cassini grazed the rings and the planet at close distances never achieved before. It returned breathtaking images, and the data gathered will feed science analyses for at least another decade. One takeaway from the Cassini end of mission is to never underestimate unknown events; three-σ change can still happen even after 13 years of mission operations. The Navigation team continued updating their process until the very end, and encountered great challenges along the way. The Cassini mission is currently working on a full mission reconstruction, from July 1st 2004 to September 15th 2017. The reconstructed trajectory will be presented at the Space Operations Conference in May 2018.

ACKNOWLEDGMENTS

Although only members of the Orbit Determination Team are listed, the whole Navigation Team should get credit for the work highlighted here. The team is also thankful to Dr. William Folkner and Dr. Robert Jacobson for providing Saturn system ephemerides and gravity products. Additional appreciation goes to the Spacecraft team, particularly the AACS team, for their constant support. The Cassini mission is operated out of the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] J. Bellerose, S. Nandi, D. Roth, Z. Tarzi, D. Boone, K. Criddle, R. Ionasescu, "Cassini Navigation: The Road to Consistent sub-Kilometer Accuracy Satellite Encounters", *AAS Guidance and Control*, AAS16-142, 2016.

[2] Cassini trajectory, https://naif.jpl.nasa.gov/pub/naif/CASSINI/kernels/spk/150901AP_SK_13290_17272.bsp.lbl, Reference trajectory 150901.

[3] P.G. Antreasian, J.J. Bordi, K.E. Criddle, R. Ionasescu, R.A. Jacobson, J.B. Jones, R.A. MacKenzie, M.C. Meek, F.J. Pelletier, D.C. Roth, I.M. Roundhill, and J. Stauch, "Cassini Orbit Determination Performance during the First Eight Orbits of the Saturn Satellite Tour", *AAS 05-312, Advances in the Astronautical Sciences* Vol 123, 2006.

[4] P. G. Antreasian, S. M. Ardalan, J. J. Bordi, K. E. Criddle, R. Ionasescu, R. A. Jacobson, J. B. Jones, R. A. Mackenzie, D. W. Parcher, F. J. Pelletier, D. C. Roth, P. F. Thompson, A. T. Vaughan, "Cassini Orbit Determination Results: January 2006 – End of Prime Mission", *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, AIAA 2008-6747, 2008.

[5] P.G. Antreasian, S.M. Ardalan, R.M. Beswick, K.E. Criddle, R. Ionasescu, R.A. Jacobson, J.B. Jones, R.A. MacKenzie, D.W. Parcher, F.J. Pelletier, D.C. Roth, P.F. Thompson, A.T. Vaughan, "Orbit Determination Processes for the Navigation of the Cssini-Huygens Mission", SpaceOps 2008 conference, AIAA 2008-3433, 2008.

[6] F.J. Pelletier, P. Antreasian, S. Ardalan, B. Buffington, K. Criddle, R. Ionasescu, R. Jacobson, J. Jones, S. Nandi, S. Nolet, D. Parcher, D. Roth, J. Smith, P. Thompson, "Cassini Orbit Determination Performance (July 2008 – December 2011)", SpaceOps 2012 conference proceedings, Col 1, p.167, 2012.

[7] M. Vaquero, Y. Hahn, P. Stumpf, P. Valerino, S. Wagner, and M. Wong, "Cassini Maneuver Experience for the Fourth Year of the Solstice Mission", *AIAA/AAS Astrodynamics Specialist Conference*, AIAA 2014-4348, 2014

[8] S. V. Wagner, "Cassini Maneuver Performance Assessment and Execution-Error Modeling Through 2015," *AAS/AIAA Space Flight Mechanics Meeting*, AAS 16-305, 2016

[9] Cassini Solstice Mission Navigation Plan, JPL Internal Document D-11621, 2010

[10] F. E. Laipert, S. V. Wagner, Y. Hahn, S. Hernandez, P. Valerino, M. Vaquero, M. C. Wong "What Goes Up Must Go Down: Cassini Maneuver Experience During the Inclination-Raising Phase Prior to the End of Mission", AAS/AIAA Space Flight Mechanics Meeting, AAS17-283, 2017.

[11] D. Boone, J. Bellerose, D. Roth, "Resolution of Orbit Determination Prediction Instabilities at Titan During Cassini's Solstice Mission", *26th International Symposium on Space Flight Dynamics*, ISSFD-2017-109, 2017.

[12] M. Vaquero, Y. Hahn, D. Roth, M. Wong, "A Linear Analysis for the Flight Path Control of the Cassini Grand Finale Orbits", *26th International Symposium on Space Flight Dynamics*, ISSFD-2017-010, 2017

[13] M. Vaquero, Y. Hahn, S. Hernandez, F. Laipert, P. Valerino, S. Wagner, M. Wong, D. Roth, "Flying Cassini Through the Grand Finale Orbits: Prediction vs. Reality", *AAS Guidance and Control*, AAS18-151, 2018.

[14] D. R. Boone, M. Wong, J. Bellerose, D. Roth, "Preliminary Saturn Atmospheric Density Results from Cassini's Final Plunge", AAS Guidance and Control, AAS18-115, 2018.